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Road safety and bicycle usage impacts of unbundling vehicular and cycle traffic in Dutch urban networks

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Bicycle-motor vehicle crashes are concentrated along distributor roads where cyclists are exposed to greater volumes of high-speed motorists than they would experience on access roads. This study examined the road safety impact of network-level separation of vehicular and cycle traffic in Dutch urban networks, a strategy for which the term 'unbundling' is used. Unbundling vehicular traffic and cycle traffic in an urban network is operationalized as the degree to which cyclists use access roads and grade-separated intersections to cross distributors. The effect on the share of cycling in the modal split is also assessed as unbundling may affect the competitiveness of cycling compared to driving in terms of trip length. The analyses were conducted on Dutch municipalities with more than 50,000 inhabitants. Negative binomial regression was used to analyse the effect on the number of police-reported cyclist deaths and in-patients in bicycle-motor vehicle crashes. A mediation model was tested, with Structural Equation Modelling hypothesizing that unbundling corresponds positively with the cycling modal share via the length of car trips divided by those by bicycle. The results of this study suggest that unbundling improves cycling safety, and increases the share of cycling in the modal split. We recommend unbundling vehicular and bicycle traffic in urban networks, e.g. establishing large traffic-calmed areas with short cuts and standalone paths for cyclists (and pedestrians) and, where feasible, grade-separated intersections such as bicycle tunnels.

Keywords: bicycle, bicycle infrastructure, bicycle usage, road network, road safety, unbundling.

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1. Introduction

Research shows that the likelihood of bicycle-motor vehicle (BMV) crashes is higher on distributor roads than on access roads (Berends and Stipdonk, 2009; Liu et al., 1995; Schepers et al., 2011; Teschke et al., 2012). Many cycling safety studies focused on separation between cyclists and motorists along distributor roads by bicycle tracks (Reynolds et al., 2009; Thomas and DeRobertis, 2013; Wegman et al., 2012). These studies, however, have not yet addressed network-level separation (Schepers et al., 2013). This form of separation can be achieved by cyclists using access roads in traffic-calmed areas and crossing distributor roads at grade-separated intersections (bicycle tunnels and bridges). Network-level separation reduces cyclists' exposure to high-speed motorists and can therefore be hypothesized to correspond positively with cycling safety. In this paper we are using the term 'unbundling', first used in this context by two native English speakers (Johnson and Murphy, 2013), to encompass the range of measures which might be used in network-level separation.

This study examines the road safety impact of unbundling vehicular and cycle traffic in Dutch urban networks. The effect on cycling's share of the modal split is also assessed as, in terms of trip length, unbundling may affect the competitiveness of cycling compared to driving. We hypothesize that increased unbundling corresponds positively with road safety and bicycle usage. Sections 1.1 and 1.2 describe literature to underpin these hypotheses. The operationalization and measurement of unbundling is further described and exemplified in Chapter 2 on data and methods. The results of a Principal Components Analysis will be presented in Chapter 3. Chapters 4 and 5 describe the results of the analyses on road safety and cycling mode share respectively. The outcomes are further discussed in Chapter 6.

1.1 Research on unbundling and road safety

This section explains the hypothesis that a higher degree of unbundling is associated with improved road safety. Dutch road safety policy is founded on the Sustainable Safety vision which was introduced at the beginning of the nineties (Koornstra et al., 1992; Wegman et al., 2008). Two of its key principles are Homogeneity and Functionality. Homogeneity implies that differences in speed, direction, and mass should not be too large, e.g. a safe speed to mix cyclist with motorized traffic is no higher than 30 km/h (Tingvall and Haworth, 1999). Functionality refers to classification of roads in a hierarchical road network. Agreement on implementation of the vision was reached in 1998, resulting in the construction of large traffic-calmed areas and the development of a hierarchical road classification by which Dutch roads are classified as access roads, distributor roads, or through roads. By 2008, the speed limit on 85% of the roads in built-up areas classified as access roads had been reduced to 30 km/h (Weijermars and Wegman, 2011). Table 1 lists the speed limits and the location of cyclists for the three classes of road.

Table 1. Road classification and speed limits in the Netherlands

Road classes	Speed limits in urban areas	Location of cyclists
Access roads	30 km/h	Mixed with other traffic
Distributor roads	50 or 70 km/h	Separated from motorised traffic by bicycle tracks or bicycle lanes*
Through roads	100 or 120 km/h	Cycling not allowed

* Tracks are physically separated from the carriageway while lanes provide a visibly delineated space on roads

Functionality concentrates motorized (through) traffic, resulting in relatively high volumes of vehicular traffic on distributor and through roads, and low volumes on access roads, which have to be (re)designed for low speeds. Application of the homogeneity principle means that cyclists on distributor roads are separated from vehicle traffic on road sections by bicycle tracks and speed reduction at intersections. Research confirms that speed reduction reduces the likelihood of BMV crashes at intersections on distributor roads (Gårder et al., 1998; Schepers et al., 2011), but

the combination of bicycle tracks and speed reduction at intersections does not seem to be sufficient to achieve low levels of BMV crashes on access roads. Even though these measures are widely applied in the Netherlands, over 80% of all police-reported fatal and severe BMV crashes in built-up areas between 2004 and 2009 occurred on 50 or 70 km/roads, i.e. on distributor roads (SWOV, 2011). This can be explained by the volumes of high-speed vehicular traffic that cyclists are exposed to on distributors, especially at intersections. Section 1.1.1 and 1.1.2 further discuss literature on road safety on distributors and in traffic-calmed areas.

1.1.1 Distributor roads

Most research on cycling safety on distributors focused on the effect of the type of bicycle facility (Wegman et al., 2012). Welleman and Dijkstra (1988) found there were 59% fewer BMV crashes on distributor road sections with bicycle tracks (including unsignalized minor intersections) as compared to those with bicycle lanes. On the other hand, they found there were 50% more BMV crashes at distributor road intersections where bicycle tracks were present. At the time the study was conducted, most of these intersections were signalized. It has been found that replacing an intersection with a roundabout reduces the number of crashes with bicycles (and mopeds) by 60% (Van Minnen, 1990).

Schepers and Voorham (2010) inspected BMV crash locations on intersections of 50 and 70 km/h distributor roads in three middle-sized Dutch cities. The results showed that around 60% of the crashes occurred at unsignalized priority intersections. Around two-thirds of cyclist casualties in BMV crashes at these intersections had been riding along the distributor (i.e. the cyclist had right of way); around one-third had been crossing the road (i.e. the motorist had priority) (Schepers et al., 2011). The risk per passing cyclist doubled when cyclists crossed a distributor as compared to when they crossed a minor road. It was found that a well-designed one-way bicycle track incorporating a deflection between 2 and 5m away from the main carriageway and speed-reducing measures could reduce the number of crashes for through cyclists. Unfortunately, no significant effects were found for road factors related to BMV crashes with cyclists crossing the distributor road (Schepers et al., 2011). Speed-reducing measures such as a speed hump did not reduce the crash risk (Schepers et al., 2011) but may reduce the injury risk (Kim et al., 2007; Wegman et al., 2012).

1.1.2 Traffic-calmed areas

A meta-analysis shows that area-wide urban traffic-calming schemes in residential areas reduce the total number of injury accidents by, on average, 25%. (Elvik, 2001). However, low-cost designs, also applied in the Netherlands during recent years, were expected to result in only a 15% reduction (Schoon, 2000). Cyclist crashes are not distinguished in these studies. An inspection of bicycle crash sites at 30 km/h access roads by Berends and Stipdonk (2009) suggested that the absence of a credible speed limit increased the risk of bicycle crashes in traffic-calmed areas. A number of BMV crashes can be prevented by speed management in residential areas where only low-cost traffic-calming measures are implemented (Weijermars and Wegman, 2011).

Provided space is available, and the above described measures have not yet been implemented, there is scope for improving cycling safety on both distributor and access roads. However, it would appear from current knowledge that the extent of the effects of existing safety measures for distributor roads is insufficient to achieve the low likelihood of BMV crashes on access roads.

1.2 Research on unbundling and bicycle use

This section explains the hypothesis that a higher degree of unbundling is associated with a higher share of cycling in the modal split. A number of studies have already addressed how the built environment affects bicycle use, e.g. high densities and mixed land use are related to increased amounts of cycling (Heinen et al., 2010). More relevant to this study is research at the network level. Research on the relationship between bicycle networks and bicycle use generally finds that factors contributing to shorter travel distances affect cycling positively (Heinen et al., 2010). As an indication of the relevance of distance, the share of cycling in the 2010 modal split in the Netherlands was around 41% for trips between 1 and 2.5 km, reducing to 33% between 2.5 and 5 km and 23% between 5 and 7.5 km (Statistics Netherlands, 2011). However, existing studies have not investigated the effect of how bicycle and pedestrian networks align with networks for through motor traffic, i.e. distributor roads (Frank and Hawkins, 2008). Frank and Hawkins (2008) focused on pedestrians in the modal split and tested for the availability of each distinct mode's networks. Providing more direct routes for walking in contrast to those for driving was found to result in an increased share of walking in the modal split. They did not study cycling. Rietveld and Daniel (2004) compared the travel times of 12-16 trips made by both bicycle and car around the city centres of 103 Dutch municipalities. They found that, in terms of travel time, increased competitiveness of the bicycle in comparison with the car increases bicycle use. It is not clear, however, to what extent network characteristics contributed to this finding; factors such as congestion also play a role in travel time.

In the Netherlands, measures to unbundle cyclist and vehicular traffic are most often combined with creation of shorter routes for cyclists, i.e. short cuts available only to non-motorized traffic and the authorization of contraflow cycling on one-way streets. Unbundling may contribute to the bicycle's competitiveness in terms of trip length and thereby increase the share of cycling in the modal split. It is not expected that unbundling is necessarily directly correlated to the amount of bicycle use. High levels of unbundling are to be expected in towns and areas built since the 1970s which often have below-average densities and less mixed land-use, factors that are found to reduce bicycle use (Heinen et al., 2010). Accordingly, the share of cycling in the modal split may even be somewhat below average in these areas, but would have been even lower had unbundling not contributed to the bicycle's competitiveness.

1.3 Study scope

This study investigates to what extent municipalities with a higher degree of unbundling have fewer cyclists hospitalized or killed following BMV crashes. The study included all 66 Dutch municipalities with more than 50,000 inhabitants, representing over 8 million people. Single-bicycle crashes are excluded as unbundling measures are not expected to have a substantial effect on such accidents. The effect on the number of casualties in car crashes is included to achieve a broader understanding of the road safety effects. The study also addresses effects on the share of cycling in the modal split. Other effects of unbundling, such as lower exposure to car exhaust fumes or reduced feelings of personal security, are not addressed in this study.

2. Data and methods

This Chapter describes the data and methods used in this study. The present study uses a correlational design to examine how the estimated degree of unbundling of vehicular and cycle traffic is related to:

- The likelihood of cyclists being injured or killed in BMV crashes

- The likelihood of being injured or killed in car crashes, excluding cyclists (to give a more general picture of the effect on road safety)
- The share of cycling in the modal split.

Unbundling is a characteristic of a municipality's urban road network that we relate to its level of road safety and modal share of cycling. The study is therefore conducted at the municipality level. Municipalities with more than 50,000 inhabitants have been selected because most of the kilometres by bicycle are travelled in urban networks.

A sample of 66 study municipalities is expected to have sufficient statistical power to reject a null-hypothesis. Power is a function of sample size and sample variance: the statistical power grows as the former increases and the latter decreases (Cohen, 1996). A low sample variance is expected in this study due to there being over 50,000 inhabitants per study unit and a study period of 6 years (between 2004 and 2009).

Section 2.1 describes the data and measurements used to determine the degree of unbundling. We complement databases for road traffic injuries and mobility data with route analyses to estimate the degree of unbundling and the competitiveness of cycling compared to driving (expressed as the length of trips by car divided by those by bicycle). Section 2.2 addresses the variables used for the analyses, and Section 2.3 describes the methods used to analyse road safety and bicycle use.

2.1 Data and measures

Police-reported crash data and mobility data from the Dutch National Travel Survey (NTS) are supplemented with the results of route analyses of trips reported in the 2008 NTS to estimate the degree of unbundling and the length of trips by bicycle and car, and the length of trips made by car compared to those made by bicycle. These data were combined with Statistics Netherlands (2011) data on population density and age of the population in Dutch municipalities, and the Netherlands slope map for altitude differences (Rijkswaterstaat, 2011a).

2.1.1 Police-reported crashes

Police-reported crash data were used to determine the level of road safety, and comprised reported cyclist victims in BMV crashes and car crash victims over a six-year period (2004-2009) across the 66 middle-sized municipalities. In the case of BMV crashes, a total of 339 deaths and 5,611 casualties admitted to a hospital were included in the analyses; car crash casualties amounted to 617 deaths and 13,389 hospitalized casualties. Crash victims on motorways are excluded. The outcomes, therefore, are relevant only for roads where cyclists are allowed.

Under-reporting is a significant problem in bicycle crash studies (Wegman et al., 2012). Reurings and Bos (2011) showed that less than 10% of seriously injured victims of crashes with no motor vehicles involved (of which around 80% are single-bicycle crashes) are recorded by the police. On the other hand, cyclists seriously injured in BMV crashes (central to this study) are more likely to be recorded by the police than seriously injured car crash victims (SWOV, 2011). Under-reporting of bicycle crashes is not expected to be problematic in this study because we do not expect that under-reporting is related to the independent variables.

2.1.2 National Travel Survey

The National Travel Survey (NTS) is used to determine the share of cycling in the modal split for trips up to 7.5 km. The NTS describes the travel behaviour of the Dutch population, and is based on a sample of households drawn every month from the Municipal Basic Administration to ensure all types of travellers and households and all days are proportionately represented. Each member of the household is requested to record all journeys made on a particular day and report

this online. Respondents are telephoned if they do not respond or to clarify missing answers, otherwise they are excluded from the final dataset (Rijkswaterstaat, 2010). Between 2004 and 2009, a total of 140,852 households (317,258 persons) completed questionnaires, corresponding to a response rate of 70.5%.

2.1.3 Operationalization of unbundling in the Dutch context

Within the context of the Dutch road classification system, unbundling is operationalized by two factors:

- The proportion of the trip length where cyclists ride on access roads, including standalone paths. The higher the proportion, the higher the degree of unbundling.
- The number of dedicated grade-separated intersections (bicycle tunnels or bridges) per kilometre travelled by bicycle. A higher number implies a higher degree of unbundling.

Figure 1 depicts an urban road network, with two routes to the same destination to illustrate the degree of unbundling.

About 50% of the route in the left-hand figure is along a distributor road. There are no grade-separated intersections. The right-hand figure shows an adapted network with larger traffic-calmed areas, several bicycle-pedestrian short cuts and a bicycle tunnel accessible by a standalone bicycle track. The degree of unbundling is highest in the right-hand figure: 100% on access roads with 1 bicycle tunnel.

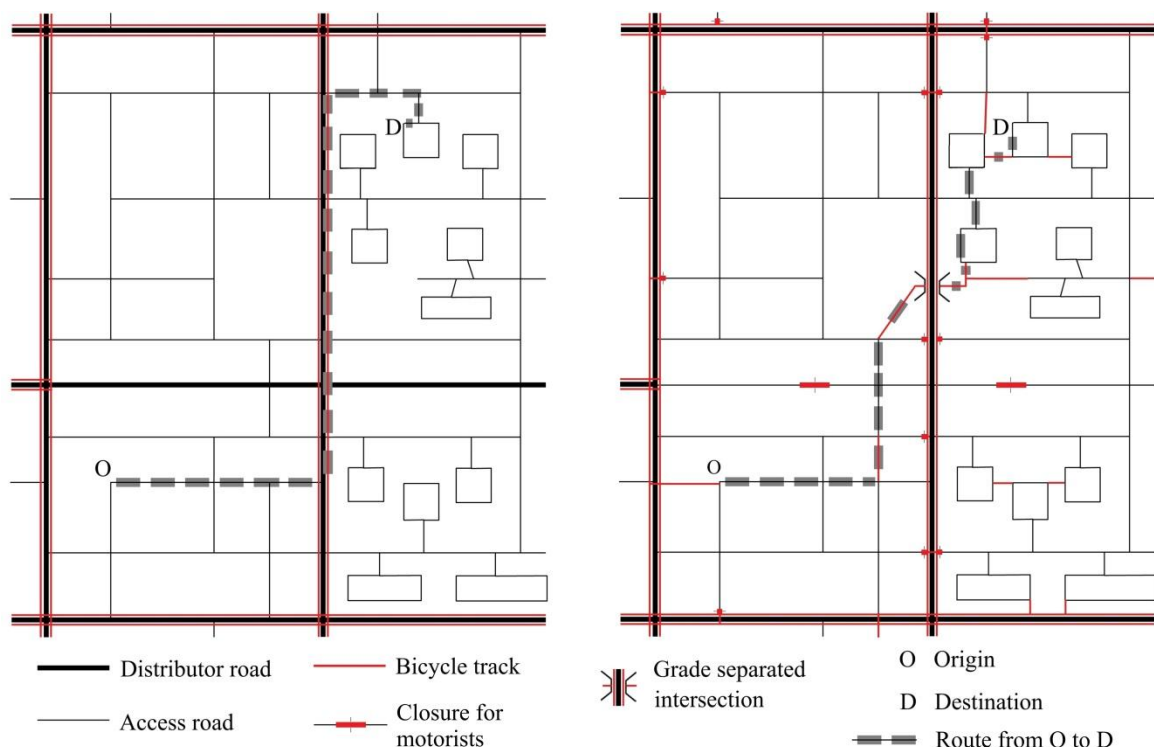


Figure 1. Examples of unbundling for two cycle routes; the degree of separation is low for the route in the left-hand figure and high for the route in the right-hand figure

2.1.4 Route analyses

In this study, route analyses were carried out on the 2008 NTS dataset to measure the degree of unbundling. The shortest route is used as a proxy for cyclist routes, while the fastest route according to route planners is used as a proxy for car routes (see Schepers and Heinen (2013) for a more extensive explanation). Special permission was given to use a dataset containing the most

detailed available ZIP codes, i.e. a six-position zip code (comprising, on average, 20 addresses) for the point of departure and return of around of one quarter of the trips, and a combination of six-position and four-position ZIP codes (consisting of on average 2,500 addresses) for the remainder. For privacy reasons, access to this dataset is not normally granted. Every first bicycle trip up to 7.5 km made each month, with a six-position zip code for the address of departure and return, was selected. This resulted in 12 trips per municipality (a total of 792 trips).

Cyclists' route choice behaviour was approximated by planning the shortest routes according to the Dutch Cyclists' Union route planner (Fietzersbond, 2011). Data about which roads are distributor roads was needed to estimate the degree of unbundling. Roads with a 50 km/h speed limit on the Dutch Speeds Map (Rijkswaterstaat, 2011b) were defined as distributor roads; roads with a 30 km/h speed limit and standalone bicycle tracks as access roads. The Dutch Cyclists' Union route planner was used to determine the share of the trip length through traffic-calmed areas and the number of grade-separated intersections, i.e. the degree of unbundling. The route planner was also used to determine the share of the trip length along distributor roads on bicycle tracks, and on standalone bicycle tracks for the other part of the trip through 30 km/h areas. Route analyses were used to determine the length of trips by bicycle and car. Car routes were approximated by planning the fastest route according to Google Maps (Google, 2011) so that the length of the same trips travelled by bicycle and by car could be compared. Route analyses of 1,152 trips in 192 municipalities conducted in the Schepers and Heinen (2013) study were used to increase the sample size for the analysis of the relationship between the proportion of cycling in the modal split and the difference in length between car and bicycle trips. The trips analysed in that study and this current study partly overlap. The total number of trips used for this study amounts to 1,528.

2.2 Methods

This section describes the variables and methods used in the analyses on road safety and bicycle use.

2.2.1 Variables

The number of deaths and hospitalized casualties among cyclists in BMV crashes and car occupants in car crashes per municipality is the dependent variable in road safety analysis. The share of cycling is the dependent variable in the analyses on the modal share of cycling. As described in the last section, the following independent variables were measured by route analyses:

- Share of the trip length through 30 km/h areas (%)
- Grade-separated intersections (no./km)
- Share of the trip length along distributor roads on bicycle tracks (%)
- Share of the trip length through 30 km/h areas on standalone paths (%)
- Trip length ratio (for the competitiveness of cycling): length of trips by car divided by those by bicycle

The first two variables define unbundling.

The presence of bicycle tracks is included as a control variable in the analyses on safety and bicycle use. A number of other variables need to be controlled in these analyses. Provision needs to be made for the control of kilometres travelled by bicycle and by car, the age of the population and population density. Important control variables for analyses on bicycle use are (Heinen et al., 2010; Rietveld and Daniel, 2004):

- The proportion of youngsters in the population, defined as inhabitants up to and including 17 years of age.
- The presence of a university.
- The presence of significant differences in altitude, defined as those greater than 50m within urban areas.
- Population density, defined in the same way as in the earlier study by Schepers and Heinen (2013): three groups, each containing one-third of all municipalities (low: < 272/km², medium 272-742/km², high: >742/km²).
- City size in terms of number of inhabitants, operationalized using three categories of municipalities determined by testing which category boundaries led to the greatest differences in bicycle use, resulting in small: <50,000; medium 50,000-175,000; high: >175,000.

To avoid over-fitting, these control variables need to be addressed without adding additional parameters to the regression analyses. This is further discussed in Section 2.2.3 and 2.2.4.

2.2.2 Data reduction

Regression analyses are conducted to estimate the effect of unbundling on safety and cycling mode share. The number of independent variables explicitly included (further described in the next section) has to align with the sample size in order to avoid over-fitting. A rule of thumb for regression analysis holds that the number of observations should be at least 20 times greater than the number of variables under study (Schneider et al., 2010). This means that a maximum of three independent variables can be included in analysis (with a sample size of 66 municipalities), and that data reduction is needed to model the above-mentioned variables. We therefore carry out Principal Components Analysis (PCA) on the variables measured in the route analyses. Besides reducing the number of variables, this step helps to avoid multicollinearity. PCA attempts to represent all of the variance of the observed variables and results in a reduced number of uncorrelated factors for regression analysis (Floyd and Widaman, 1995; Garson, 2012).

2.2.3 Negative Binomial regression for road safety analyses

Using Generalized Linear Models in SPSS, Negative Binomial (NB) regression was carried out to test the effect of unbundling on numbers of police-reported crash victims. The basic form of nearly all modern accident prediction models used for NB regression is (Eenink et al., 2008):

$$E(\mu) = \alpha V_M^{\beta_1} V_C^{\beta_2} e^{\sum y_i x_i} \quad (1)$$

The expected number of bicycle crash victims, $E(\mu)$, is a function of traffic volumes of motor vehicles (VM) and cyclists (VC) and a set of risk factors, x_i ($i = 1, 2, 3, \dots, n$). The coefficient α is a scaling parameter, which ensures that the predicted number of crashes is in the same range as the police-reported number of crashes. Coefficients β_1 and β_2 describe the shape of the relationship between traffic volume and victim numbers. The effects of various risk factors that influence the probability of crashes, given exposure, is modelled as an exponential function, that is as e (the base of natural logarithms) raised to a sum of product of coefficients, y_i , and values of the variables, x_i , denoting the presence of risk factors.

NB regression serves as statistical approximation to the crash process (Lord et al., 2005). Although the Poisson model has served as a starting point for crash-frequency analysis for several decades, researchers have often found that crash data exhibit over-dispersion (i.e. the variance exceeds the mean), which makes the application of the simple Poisson regression problematic. NB regression, which is now the most frequently used model in crash-frequency

modelling, overcomes this problem (Lord and Mannering, 2010) and accordingly has been used in this study.

Because of the number of observations involved, applying the above-described form of model, including all control variables, results in too large a number of independent variables. In linear regression analysis and Structural Equations Modelling, researchers statistically partial out the effects of control variables from the model variables and then test the model in order to avoid too complex a model. This method is not an option in the case of NB regression, where the values of the dependent variable are count data. Therefore, the authors first predicted the number of cyclist and car crash deaths and in-patients by using the Accident Prediction Models (APMs) developed in an earlier study (Schepers and Heinen, 2013). These comprised the following variables:

- Kilometres travelled by bicycle and by car (excluding kilometres travelled on motorways).
- Age of cyclists and car crash victims.
- Population density of the municipalities.

APMs were developed for the same study period (2004-2009) and for a larger set of 387 municipalities (see Schepers and Heinen, 2013). The number of victims predicted by the APMs, EAPM, is included as an offset. The model that will be tested in this study has the following form:

$$E(\mu) = \alpha E_{APM} e^{\sum y_i x_i} \quad (2)$$

The expected number of victims, $E(\mu)$, is a function of an offset, EAPM, multiplied by e raised to a sum of product of coefficients, y_i , and values of the factors under investigation, x_i .

2.2.4 Structural Equation Modelling for analyses on bicycle use

The indirect effect between unbundling and the cycling modal share via the length of trips by car divided by those by bicycle is tested using Structural Equation Modelling (SEM) in SPSS Amos. As with the road safety analyses, the availability of bicycle tracks will be included explicitly in the model as a control variable. SEM uses covariance analysis whereby model parameters are determined such that variances and covariances of the variables implied by the model system are as close as possible to the observed variances and covariances (Golob, 2003). The size of the indirect effect between the degree of unbundling and the share of cycling is the product of path coefficients. We conducted Sobel's (1982, 1988) test to examine whether the indirect effect is significant.

Other control variables important to the amount of cycling were partialled out of the covariance matrix prior to analysis. The technique for partialling out the effects of one or more (control) variables from other variables in order to find the relationship between them is called partial correlation. For example, Ley (1972) describes a researcher interested in the relationship between variables A and B, with the effects of C partialled out from both. He would have to correlate the residual scores of A and B, after the parts of A and B predictable from C have been subtracted. This results in a partial correlation between A and B (controlled for variable C). In our study, the controls were partialled out instead of being explicitly modelled because the latter would have resulted in a high number of independent variables.

Note that the path between trip length ratio and the share of cycling is determined using additional data from the cases in the study by Schepers and Heinen (2013). This increases the sample size for this relationship in the path model to 192. Data on the degree of unbundling and availability of bicycle tracks was available for 66 of these 192 municipalities. The other path coefficients are therefore determined using the 66 cases (for which route analyses are conducted in this study) and treating the other cases as missing values.

3. Data reduction

This Chapter describes the Principal Components Analysis (PCA) to reduce the number of variables measures in the route analyses. Trip length ratio (length of trips by car divided by those by bicycle) is not included in the PCA. This variable needs to be included explicitly in the SEM analysis to test the indirect effect of unbundling on bicycle mode share.

Table 2 shows the means, standard deviations, and correlations for the 4 route analysis variables. The results of the route analyses suggest that cyclists travel around two-fifths of bicycle kilometres in built-up areas on distributor roads and three-fifths through traffic-calmed areas. Per kilometre, cyclists on average pass 0.1 grade-separated intersections such as bicycle tunnels and bridges. The correlations show that both variables defined to operationalize the degree of unbundling (share of the trip length through 30 km/h areas and the number of grade-separated intersections per km) are highly correlated (a correlation coefficient of 0.58). Including both variables in the regression analyses results in biased parameter estimates due to multicollinearity. The results of NB regression analyses (using the four variables in the upper part of Table 2) indicated large changes in the estimated regression coefficients when either of the two highly correlated variables was added or deleted. This problem is avoided by using PCA.

Based on the Kaiser-Guttman criterion (eigenvalue > 1), two factors could be retained in the PCA that together explain 76% of the variance of the observed variables. These have been included in Table 2 as the Degree of unbundling and the Availability of bicycle tracks (along both distributor roads and standalone paths through residential areas). Positive factor figures indicate higher degrees of separation and ample availability of bicycle tracks. The varimax-rotated solution is shown in Figure 2. The share of the trip length along distributor roads and the number of grade-separated intersections per km both have factor loadings greater than 0.80 on the unbundling factor and low factor loadings on the bicycle tracks factor. The share of the trip length on bicycle tracks along distributor roads and the share of the trip length on standalone paths in 30 km/h areas have factor loadings greater 0.65 on the bicycle tracks factor and lower loadings on the unbundling factor. The share of the trip length on standalone paths through 30 km/h areas has, besides a loading of 0.66 on the bicycle tracks factor, also a loading of 0.54 on the unbundling factor. This may result from the fact that standalone paths are often used in conjunction with bicycle tunnels and bridges to give cyclists access to grade-separated intersections. The unbundling factor score thus consists of the share of the trip length where cyclists ride along distributor roads, the number of grade-separated intersections per km and, to a lesser extent, the availability of standalone paths.

The route analyses variables that will be explicitly included in the road safety analyses are:

- Degree of unbundling of vehicular and cycle traffic based on 66 municipalities.
- Availability of bicycle tracks based on 66 municipalities.

These route analyses variables will be included in the analysis on bicycle usage as well, next to the trip length ratio based on 192 municipalities (see Section 2.2.4).

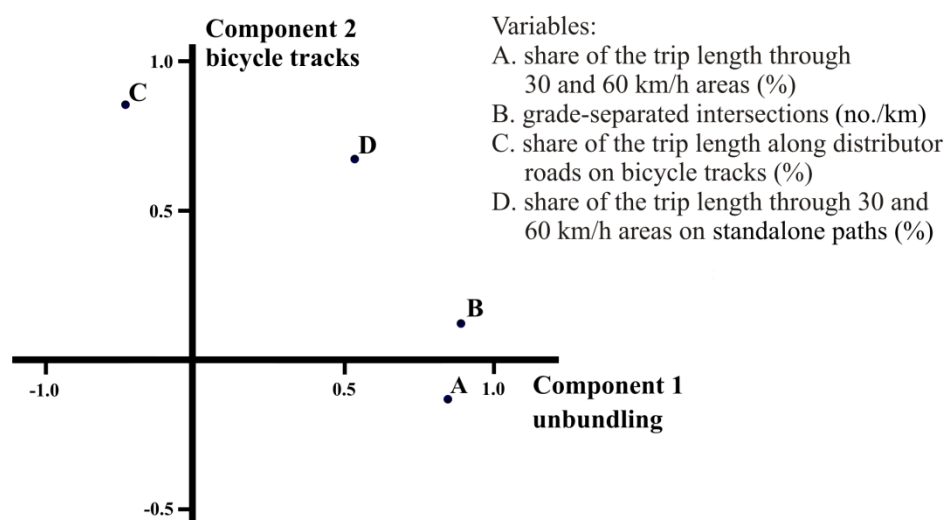


Figure 2. Factor loadings of the four independent variables on the unbundling and bicycle tracks factor

Table 2. Descriptive Statistics for the Route Analysis Variables (N=66)

	Mean	SD	Correlations					
Variables			1.	2.	3.	4.	5.	6.
Independent variables:								
1. Share of the trip length through 30 km/h areas (%)	59.2	11.9	1	0.58**	-0.14	0.23	0.84**	-0.14
2. Grade-separated intersections (no./km)	0.1	0.1		1	-0.07	0.43**	0.88**	0.09
3. Share of the trip length along distributor roads on bicycle tracks (%)	59.5	19.8			1	0.25*	-0.20	0.88**
4. Share of the trip length through 30 km/h areas on standalone paths (%)	15.3	10.1				1	0.54**	0.66**
Factor scores:								
5. Degree of unbundling	0	1					1	0.00
6. Availability of bicycle tracks	0	1						1

* $p < 0.05$ (two-tailed)

** $p < 0.01$ (two-tailed)

4. Results of road safety analyses

This Chapter describes the results of the road safety analyses conducted to test the hypothesis that unbundling corresponds positively with cycling safety. Table 3 shows descriptive statistics. Per municipality, around 5 cyclists were killed and 85 were hospitalized in police-reported BMV crashes between 2004 and 2009. The numbers of reported casualties in car crashes (excluding cyclists) amounted to 9 deaths and 203 hospitalizations.

Table 3. Descriptive Statistics for the Variables Used in the Crash Analyses

	Mean	SD	Correlations					
Variables			1.	2.	3.	4.	5.	6.
Crash victims 2004– 2009:								
1. Cyclist deaths in BMV crashes	5.1	2.8	1	0.81**	0.68**	0.78**	-0.28*	-0.02
2. Cyclist hospitalizations in BMV crashes	85.0	39.6		1	0.68**	0.90**	-0.27*	-0.04
3. Deaths in car crashes (excluding cyclists)	9.3	5.3			1	0.83**	-0.27*	-0.14
4. Hospitalized casualties in car crashes (excluding cyclists)	202.9	171.0				1	-0.30*	0.00
Factor scores:								
5. Degree of unbundling	0	1					1	0.00
6. Availability of bicycle tracks	0	1						1

* p < 0.05 (two-tailed)

** p < 0.01 (two-tailed)

The results of NB regression analyses on police-reported crash victims between 2004 and 2009 are shown in Table 4. The results show that the likelihood of cyclists being hospitalized or killed due to BMV crashes is lower in municipalities with a higher degree of unbundling. The availability of bicycle tracks is not found to be related to the crash likelihood. The regression coefficients can be interpreted as follows. The coefficient for unbundling in the regression analysis of cyclist deaths is -0.27, meaning that an increase in an unbundling score of 1 (or 1 Standard Deviation as the factors are standardized variables) in a given municipality leads to a reduction of 24% (1 minus $\exp(-0.27)$ in the likelihood of being killed in BMV crashes). Likewise, the likelihood of cyclists being hospitalized in BMV crashes decreases by 15%. The likelihood of car crash victims being hospitalized is also significantly lower in municipalities where the degree of unbundling is higher (a difference of 12%). The likelihood of being killed in car crashes is also associated with unbundling, but this is only significant at the 10% level.

Table 4. Estimation results for regression on police-reported crash casualties (95% Wald CI)

Variables	Cyclist victims in BMV crashes		Victims in car crashes (excluding cyclists)	
	fatalities	hospitalized	fatalities	hospitalized
Casualty numbers in the 66 municipalities	339	5,611	617	13,389
Regression parameters for:				
Degree of unbundling	-0.27 (-0.47 to -0.07)*	-0.16 (-0.25 to -0.06)**	-0.10 (-0.22 to 0.01)	-0.13 (-0.20 to -0.06)**
Availability of bicycle tracks	0.01 (-0.17 to 0.19)	-0.03 (-0.12 to 0.06)	-0.11 (-0.23 to 0.02)	-0.01 (-0.09 to 0.07)
Log likelihood	-169.7	-349.7	-206.0	-404.2

* p < 0.05 (two-tailed)

** p < 0.01 (two-tailed)

5. Results of analyses on bicycle use

This Chapter describes the results of the analyses conducted on bicycle mode share to test the hypothesis that unbundling corresponds positively with bicycle usage. Table 5 shows descriptive statistics of the variables used in the analyses. The average share of cycling in the modal split for trips up to 7.5 km is 34%. It ranges between 12 and 49% in the 66 municipalities for which route analyses were conducted. Trips are, on average, 20% longer by car than by bicycle (ranging between 6 and 51%). The degree of unbundling and availability of bicycle tracks are factor scores with an average of zero and standard deviation of 1. Two new towns (Lelystad and Almere) have the highest degrees of unbundling.

SEM was used to test the mediation model shown in Figure 3. The model comprises the indirect effect of unbundling on cycling mode share via the trip ratio, and the bicycle tracks factor. The effects of variables 5 – 11 have been partialled out of the model variables 1 – 4. The results show that the specified model provided an acceptable fit to the data, indicated by a Chi-square statistic that was not significant ($\chi^2(1, N=192) = 0.002, p=0.96$). The CFI value was 1.00. A rule of thumb for CFI is that a good model should exhibit values greater than 0.90 (Golob, 2003).

The path coefficients are shown in Figure 4. A higher degree of unbundling is related to a higher ratio for the length of trips by car divided by those by bicycle ($\beta = 0.29, p < 0.01$), this being related to a higher share of cycling in the modal split ($\beta = 0.19, p = 0.01$). None of the coefficients of the paths from bicycle tracks to other variables is significant. The indirect effect of the degree of unbundling via the trip length ratio on the share of cycling can be estimated to 0.06 (0.29 multiplied by 0.19). The two-tailed Sobel test showed that the indirect effect was almost significant ($t = 1.86, p = 0.063$). While this small indirect effect is in line with the hypotheses, the result is only significant at the 10% level. The statistical significance is further discussed in Chapter 6.

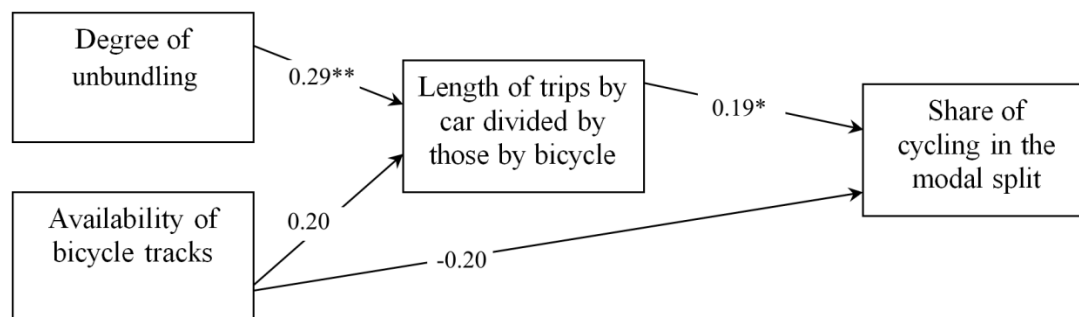


Figure 3. Structural model with standardized parameter estimates (* $p < .05$. ** $p < .01$; two-tailed)

6. Conclusions and discussion

This study, using data at the municipality level, examined the effects on road safety and bicycle use of unbundling vehicular and cycle traffic in urban networks. A higher degree of unbundling is associated with cycling through traffic-calmed areas and grade-separated crossing of distributor roads, i.e. by bicycle bridges and tunnels. Cyclists can be guided to these structures by use of standalone paths through residential areas. The results of this study suggest that:

- municipalities with a higher degree of unbundling have fewer cyclist casualties (hospitalized or killed) in BMV crashes;
- measures taken for unbundling tend to improve the competitiveness of cycling (car trips become longer relative to the same trips made by bicycle), thereby slightly increasing the share of cycling in the modal split.

The positive effect on cycling safety can be explained by the fact that cyclists are exposed to lower numbers of motorists in municipalities where there is a greater degree of separation between them. The likelihood of car crash victims (cyclists excluded) being hospitalized is also significantly lower in municipalities where the degree of unbundling is higher (the effect is smaller than for cyclist casualties). Other road users' safety also benefits from measures such as large traffic-calmed areas associated with unbundling. The small positive effect on bicycle use can be explained by the improved competitiveness of cycling compared to driving. The trip length by bicycle becomes relatively shorter than the same trip made by car due to measures such as short cuts where roads are closed to motor vehicles, authorization of contraflow cycling on

one-way streets (SWOV, 2010). The finding that reducing lengths of trips by bicycle compared to those by car is related to the share of cycling in the modal split aligns with earlier research by Rietveld and Daniel (2004), who found that competitiveness in terms of travel time plays an important role in bicycle use.

Table 5. Descriptive Statistics for the Variables Used in the Bicycle Usage1

Variables	Mean	SD	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
1. Share of cycling in the modal split for trips up to 7.5 km	34.0	7.1	1	0.12	0.07	-0.17	0.35**	-0.10	-0.01	0.01	-0.06	0.03	-0.37**
2. Length of trips by car compared to by bicycle	1.2	0.1	0.15*	1	0.26*	0.15	-0.13	-0.12	0.29**	0.18*	0.17*	0.12	-0.03
3. Degree of unbundling	0.0	1.0	0.04	0.24*	1	0.00	0.18	0.19	-0.15	0.01	-0.01	-0.11	-0.13
4. Availability of bicycle tracks	0.0	1.0	-0.16	0.16	-0.02	1	0.03	-0.03	0.01	0.00	0.00	-0.20	-0.18
5. Share of youngsters in the population (% up to 17 years of age)	22.6	2.4					1	0.01	-0.19**	-0.19**	-0.16**	-0.33**	-0.29**
6. Medium population density (272-742/km ²)	33.1	47.1						1	-0.50**	-0.16**	-0.10*	-0.13*	0.08
7. High population density (>742/km ²)	33.3	47.2							1	0.41**	0.21**	0.25**	0.04
8. Medium size (50.000-175.000 inhabitants)	15.0	35.7								1	-0.06	0.13**	0.10*
9. Large size (> 175.000 inhabitants)	2.1	14.2									1	0.60**	-0.02
10. Presence of a university	3.1	17.4										1	0.15**
11. Presence of large altitude differences (>50m within built-up areas)	2.8	16.6											1

1 correlations above the diagonal are for raw scores; correlations below the diagonal are partial correlations that have variables 5-11 partialled out

* p < 0.05 (two-tailed)

** p < 0.01 (two-tailed)

Because of its positive effects on road safety and bicycle usage, we recommend the unbundling of motor and cycle traffic in urban networks (see also Furth (2012) and Van Boggelen et al. (2011) for recommendations concerning the implementation). Another argument in support of unbundling is the outcome of a recent study by Jarjour et al. (2013), indicating that unbundling decreases cyclists' exposure to vehicle-related air pollutants. According to De Hartog et al. (2010), the health effects of inhaled air pollution can be as serious as those of traffic accidents.

6.1 The statistical significance of the results regarding cycling modal share

It was hypothesized that unbundling corresponds positively with the cycling modal share via the length of car trips divided by those by bicycle. It can therefore be argued that the null-hypothesis has to be tested using a one-tailed probability because the hypothesis clearly states the direction of the effect (Heiman, 1999). The one-tailed probability of the indirect is significant (p = 0.031), which supports the hypothesis. Chapter 5 presented only the two-tailed Sobel test which was almost significant (p = 0.063).

6.2 Effect of more cycling on road safety

The road safety effect of unbundling was determined using Accident Prediction Models (APMs) to control the kilometres travelled by bicycle and car in each municipality, i.e. the results reflect *ceteris paribus* effects. However, policies to separate cyclists from the distributor road network tend to increase the share of cycling in the modal split. Results from two recent Dutch studies estimating the effect of an increased share of cycling in the modal split suggest that transferring short trips made by cars to bicycles does not change the number of fatalities (Schepers and Heinen, 2013), or leads to only a small increase (Stipdonk and Reurings, 2012). Both studies suggest a greater increase in the number of hospitalized casualties as a result of more single-bicycle crashes (see also Schepers, 2012). The road safety effects of unbundling are found to be strong and robust, whereas its effects on the share of cycling in the modal split are small. It is therefore expected that the direct effects of unbundling on road safety, as identified in this study, will be more numerous than the additional indirect effects of more cycling.

6.3 Study limitations and recommendations for future research

A strength of this study compared to earlier studies conducted at a spatially aggregated level is that an empirically-based measure of traffic volumes per municipality could be derived from the NTS. This is important because volumes explain the largest part of the systematic variation in crash frequency (Brüde and Larsson, 1993). Researchers often have to rely on proxies for bicycle use per spatial unit, based on population per square mile, numbers of employed, number of school children, etc. (e.g. Siddiquia et al., 2012; Vandenbulcke-Plasschaert, 2011). However, a limitation of the NTS is that kilometres travelled in municipalities cannot be split between kilometres travelled inside and outside city limits. The APMs developed in the Schepers and Heinen (2012) study – also used for this study – are developed to estimate the casualty numbers inside and outside city limits. This is disadvantageous because the current study focuses on an issue within city limits. The effect on the outcome is expected to be minimal because we selected municipalities with over 50,000 inhabitants where the largest part of the population lives within city limits. Of the police-reported cyclist fatalities between 2004 and 2009 in the municipalities in our sample, almost 85% occurred within city limits. The figure for police-reported hospitalized cyclists was over 90% (SWOV, 2011), meaning that only between 10 and 15% of casualties are most likely unaffected by unbundling. This means that, because BMV crashes outside city limits are not likely to be affected by unbundling, the effect of unbundling may be even greater than found in our study. Future research could consider estimating volumes within city limits (e.g. by using multi-modal traffic models) to analyse the effect of unbundling (CROW, 2007).

Another reason for not drawing firm conclusions on size of the effect is that it depends on the composition of measures adopted by road authorities. For instance, traffic-calmed areas may differ in size and the extent to which motor vehicle speed is successfully reduced. This indicates that the effect of such measures may differ in quality, which makes it even more difficult to study how such measures contribute to the effects of unbundling. While winding residential streets may successfully lower speed, they may also decrease the recognisability of routes for cyclists. This may reduce the likelihood of them choosing routes through such areas, but it could be countered by a recognizable network of more direct standalone bicycle tracks, etc. This suggests that the success of an unbundling strategy depends on how well the measures are aligned. Isolating and quantifying the effects of individual measures may be difficult and may deny the importance of the combined effect of a range of measures to overall effectiveness. However, it could be valuable to focus on the most important elements and their relative importance, e.g. routes through traffic calmed areas vs. grade-separated intersections to cross distributors.

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